Geological Aspects of Potential Rail Line Rerouting, Southern Minnesota, and Western South Dakota

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GEOLOGICAL ASPECTS OF POTENTIAL RAIL LINE REROUTING, SOUTHERN MINNESOTA AND WESTERN SOUTH DAKOTA

This section of the report provides an evaluation of geological conditions affecting the feasibility of railroad routing as it would affect the construction and operation of the railroad at several locations in southern Minnesota and western South Dakota. The areas addressed include the proposed railroad line to bypass Rochester, the proposed railroad line to bypass Mankato, the construction of a new railyard between Utica and Lewiston, and the proposed new rail section to be constructed on exposures of a particular geologic formation (the Pierre Shale) in South Dakota proposed in the Draft Environmental Impact Statement – Powder River Basin Project, (by the Surface Transportation's Board's Section of Environmental Analysis, September, 2000).

In this geological evaluation, five major aspects of the site geology that are considered relevant to the feasibility of railroad construction and operation are considered: karst topography (as it pertains to the presence of sinkholes and the potential for formation of new sinkholes), the potential for contamination of groundwater, the potential for changes in the groundwater flow regime of the area, slope stability, and constructability on shale.

The geologic setting of the region, as well as details of the local geology along the two alternative railroad routes, the area of the proposed new railyard, and the proposed new line in western South Dakota are described in order to allow evaluation of these issues, because, to a large extent, the geology controls sinkhole formation and occurrence, the susceptibility of the groundwater to pollution due to surface spills, the groundwater flow pattern, slope stability of new excavations, and the design for construction on a shale formation.

Following the section describing the general geologic settings of Rochester and Lewiston, an evaluation is made of the karst conditions along the existing line and the proposed bypass routes at Rochester and the proposed area of the new railyard near Lewiston. This is followed by a section describing the general geologic setting near Skyline (Mankato), Minnesota and the feasibility of constructing the line near Skyline. The final section of the report describes the general geologic setting of western South Dakota and the constructability of the rail line on outcrops of a particular geologic formation noted for slope stability problems, the Pierre Shale. All discussions will conclude with mitigating measures that could be employed to reduce risks related to each geological condition.

REGIONAL GEOLOGIC SETTING-ROCHESTER AND LEWISTON

The following sections of this report provide a description of the soil overburden, the bedrock strata, and the groundwater occurrence of this region, because they control any evaluation of potential design of a major engineered structure such as a railroad.

The near-surface geology of the region includes two principal geologic units: Cenozoic age unconsolidated overburden comprising primarily glacial drift, and Paleozoic Age bedrock strata comprising chiefly limestone, shale, and sandstone. Groundwater occurs in the more highly permeable layers within each of these units.

Overburden

The city of Rochester and surrounding areas, along the route of the proposed Rochester bypass, are located in Olmsted County, while the area of the proposed new railyard between the cities of Utica and Lewiston is located in Winona County. The unconsolidated overburden soils that occur in much of Olmsted and Winona Counties comprises primarily glacial deposits ("drift") of both till and outwash deposits, with some wind deposited silt (loess). Tills in Olmsted County are primarily silt and clays with a significant mix of sand, gravel and boulders within the matrix of fines. Tills in Winona County are basically the same, with the till consisting of loam to clay loam with scattered pebbles, cobbles, and boulders. Tills were deposited primarily as ice-contact deposits, bulldozed into place by advance of glacial ice sheets during the last ice age. Outwash comprises primarily sands and gravels deposited by flowing glacial meltwater streams at the end of the ice age.

Glacial drift deposits are therefore highly variable in lithology, ranging from clays and silts to sands and gravels. Since most of southeastern Minnesota was missed by the latest glacial event, and parts of the area around Olmsted and Winona Counties are considered driftless, the glacial deposits are relatively thin, typically ranging from zero to about fifty feet thick above the bedrock surface in different parts of the county. West of Rochester the drift thickens substantially, where it can be as much as 250 feet thick. In central Winona County, the drift is generally 20 to 50 feet thick, and 10 to 20 feet thick in the eastern part of the county. Locally, where the drift primarily comprises fine-grained materials, it is an aquitard (confining layer). Where it consists of sands and gravels, it locally comprises an aquifer. The thicker the drift, the more probable that it is acting as a confining layer, due to the predominance of fine grained materials within the drift.

Because the upland areas surrounding Rochester and Lewiston have very little glacial drift, bedrock exposures are common, particularly along the streams and rivers of the area. Recently deposited river alluvium consisting of silt, sand and gravel locally comprises the uppermost unconsolidated overburden or fill of the valley floors.

Based on the Map of Surficial Geology of Olmsted County (Hobbs, H.C., 1988, sheet 3 of the Geologic Atlas of Olmsted County) approximately the eastern half of the existing rail line transects areas of shallow bedrock (less than five feet of overburden) and multiple patches of ground where the glacial till overburden is slightly thicker (over five feet thick). In the central part of the line, primarily in the city of Rochester, the surficial soils are predominantly terrace deposits and alluvium. For a stretch of line several thousand feet long at the western end of the existing route, the surficial soils comprise loess and till over five feet thick.

Based on the Map of Surficial Geology of Winona County (Hobbs, H.C., 1984, sheet 3 of the Geologic Atlas of Winona County) the area proposed for the new railyard near Lewiston consists of shallow bedrock overlain by loamy till commonly no more than 10 feet thick, but in places it ranges up to 25 feet thick. In many places, the till has been eroded by slope wash and stream erosion and only a layer of gravel remains above the bedrock and under the loess. The till is generally thickest along drainage divides and thin or absent on the upper rims of valleys. The till is covered by a silty-loam loess and is commonly no more than 10 feet thick but could range up to 18 feet thick along drainage divides and thins to less than a foot near the edges of deep valleys.

The proposed bypass route for Rochester transects three different areas where the generalized soil overburden conditions can be summarized as follows. Approximately the eastern third of the bypass route crosses an area where the soil overburden is typically five feet thick or less. A portion of this segment is where the known sinkholes are concentrated in this area. The central third of the line crosses an area where approximately five feet or more of loess (wind deposited silt) mantles the bedrock, and glacial till also occurs above the bedrock. Some known sinkholes also occur in this geologic setting. Approximately the western third of the route is in an area where at least five feet of glacial till, with a thin layer of loess overlies the bedrock. Only scattered sinkholes are noted in this area.

In all three settings, the proposed bypass route crosses localized patches of terrace deposits and narrow bands of alluvium in the bottoms of stream valleys.

The proposed location of the railyard near Lewiston lies in an area of thin layers of loess and till, (potentially no more than 20 to 35 feet thick combined) which overlies highly solutioned dolomite. The proposed western end of the railyard would be present in an area that has the highest elevation and yield of shallow groundwater. The high discharge rate of this bedrock may aggravate the formation of sinkholes and as shown on the Sinkholes and Sinkhole Probability Map (Dalgleish, J. B., and Alenander, Calvin, Jr. 1984, sheet 5 of the Geologic Atlas of Winona County), a large cluster of sinkholes is present on the western end of the proposed railyard.

Bedrock

The upper bedrock units, which occur in the interval from at or near the ground surface to 1,000 feet below ground are made up of marine sedimentary rocks of early Paleozoic age. From the youngest to oldest, the principal shallow bedrock strata within the region include:

Maquoketa Shale and Dubuque Formation: These units occur only in a small portion of the southwestern corner of Olmsted county. Only about 20 feet of the lower beds of the lower member are present. They consist of mainly buff-colored argillaceous silts, sandy shale, and impure limestones, which yield a small amount of drinking water for domestic and farm use.

Galena Group: Subdivided into three principal units, from the top down, the Stewartville Formation, primarily a fine grained dolomite and dolomitic limestone showing pitting where exposed and crinkly bedding where there are fresh surfaces with extensive bioturbation, the Prosser Limestone, which is widely exposed and consists of a very fine grained, thin bedded limestone that becomes dolomitic near the top, and the Cummingsville Formation which is a very fine grained limestone and interbedded calcareous shale which decreases upward in the unit. This group makes up the upper carbonate aquifer for the Olmsted County located on the south and southwest areas of the county. It appears that the Stewartville and the upper portion of the Prosser are the most susceptible to karst. _Only the lower unit of this group is found as cap to a plateau in the farthest southwest corner of Winona County.

Decorah Shale: This green calcareous shale contains thin interbeds of limestone and is commonly very fossiliferous but is poorly exposed in both counties and most likely covered in grass.

Platteville Formation: This highly exposed unit consists of a fine-grained, fossiliferous gray limestone which contains thin shale partings near the top. Found beneath the higher uplands, this unit yields moderate volumes of water.

Glenwood Formation: A green sandy shale which is exposed as the crests of escarpments which tend to be grass covered.

St. Peter Sandstone: It is made up of fine to medium grained friable sandstone; well sorted and poorly cemented. Weathered surfaces will be hardened and exhibit a gray to black color unlike the unweathered color of bright white. The unit is highly exposed in Olmsted County and in the southwest corner of Winona County. Significant quantities of groundwater may occur within the pore space between the grains of this sandstone.

Prairie du Chien: consists of two formations; the Shakopee and the Oneota Dolomite. The thin to medium-bedded dolomite of the Shakopee contains thin interbeds of quartzose sandstone and shale, and fine-grained quartzose sandstone occurs at the base of the formation. The Oneota Dolomite is thick bedded to structureless and becomes sandy in the lowest 15 to 20 feet. These formations are the uppermost bedrock unit for a major portion of the northern half of Olmsted County and the central portion of Winona County.

Jordan Sandstone: This formation is exposed very rarely in Olmsted and is exposed minimally in Winona County on the upper slopes of the stream valleys that drain to the Mississippi River on the northern edge of the county and streams that drain the southern edge of the county. It is made up of friable to well cemented, fine to coarse-grained sandstone from the upper portion of the unit to the lower. Significant quantities of groundwater may occur within the pore space between the grains of this sandstone. Beneath the Jordan is a confining siltstone unit of up to 75 feet thick called the St. Lawrence.

St. Lawrence and Franconia Formations: These formations are made up of a thin-bedded dolomitic siltstone and sandstone with minor shale partings. The St. Lawrence Formation can range from 50 to 75 feet thick and the Franconia can range from 140 to 180 feet thick. These units are exposed in Winona County on the slopes of the stream valleys that drain to the Mississippi river and areas south of the county, as well as in Olmsted county in two stream valleys on the northern and easter boundaries of the county.

Ironton & Galesville Sandstones: The Ironton is a poorly sorted, silty, fine- to medium- grained quartzose sandstone with minor glauconite. The Galseville is a fine- to medium-grained, well sorted quartzose sandstone. Both sandstones are only exposed in Winona County deeper in the stream valleys that drain the county to the north and south.

Eau Claire Formation: This unit is not exposed in either county and is present beneath the overburden in the Mississippi river valley on the northern edge of Winona County. It consists of a very fine to fine-grained sandstone and siltstone with some being glauconitic and interbedded with shale.

Mt. Simon Sandstone: This fine to very coarse grained, poorly cemented sandstone is present beneath the floor of Mississippi River Valley. It underlies approximately 200 feet of overburden, and its basal contact is a major erosional surface.

The position of these strata within the entire stratigraphic column for Olmsted county is shown in Figure 1, which is excerpted from the report entitled Hydrogeology and Simulation of Groundwater Flow in the Rochester Area, Southeastern Minnesota, 1987 – 1988, (Delin, G.N., US Geological Survey, 1991). As can be seen on that figure, the formations are grouped into designated aquifers and confining units. The portion of these strata within the stratigraphic column for Winona county is excerpted from Plate 2 of the Geologic Atlas of Winona County, Minnesota, 1984, (University of Minnesota, 1984) and can be seen as Figure 2 of this report.

The map of Bedrock Geology of Olmsted County (Olsen, B.M., 1988, sheet 2 of the Geologic Atlas of Olmsted County) and the map of Bedrock Geology of Winona County (Mossler, J. H., and Book, P. R., 1984, sheet 2 of the Geologic Atlas of Winona County) shows the distribution of these strata, where they either outcrop or subcrop beneath the unconsolidated overburden. The youngest of these Paleozoic strata typically occur beneath the upland portions of the county but have been removed by erosion from the major valleys and lowlands. Thus, in Olmsted County the Maquoketa and Dubuque occur only in the southwestern part of the county, but these units have been eroded off farther north, where the Galena then comprises the uppermost bedrock. In Winona County the Galena, Decorah, Platteville, Glenwood, and St. Peter occur only in the southwestern part of the county, but these units have also been eroded off farther north and east where the Prairie du Chien comprises the uppermost bedrock.

Within the major stream valleys of Olmsted County, the Galena has also been removed by erosion, exposing the Decorah, and below that, the Glenwood, St. Peter, Platteville, and Prairie du Chien in succession in the lower parts of the valley walls and floors where erosion of the valley cut deepest. Within the major stream valleys of Winona County, the Galena, Decorah, Platteville, Glenwood and St. Peter have been removed by erosion, exposing the Prairie du Chien, Jordan, St. Lawrence and Franconia in succession in the lower parts of the valley walls and floors where erosion of the valley cut deepest.

Stream drainage in both counties has greatly affected the topography of the bedrock. The channels tend to follow the jointing and fractures in the bedrock, which caused them to trend northwest to southeast and northeast to southwest. Glacial drift has filled some of the older channels so that the newer channels may follow a different orientation. Stream erosion has shaped the topography as it relates to the more resistant formations (i.e. the Galena Group and the Prairie du Chien Group), forming plateaus separated by escarpments by the erosion of the Decorah Shale, Platteville Limestone and Glenwood Shale and the St. Peter Sandstone. The Platteville is fairly resistant, but when the layers surrounding it are eroded, the Platteville is quite erodable and blocks of it will topple, and a new erosional path will be created further back in the formation.

Groundwater Occurrence

As shown on Figures 1 and 3, the geologic strata in both Olmsted and Winona Counties have been designated as aquifers and confining units. The karst conditions of concern for this project occur within the Upper Carbonate Aquifer of each county. This aquifer is a local source of groundwater to individual wells. The City of Rochester's source of drinking water is from the next deeper aquifer - the St. Peter-Prairie du Chien-Jordan aquifer (hereinafter referred to as the St. Peter). Much of the drinking water for the western portion of Winona county is also the Prairie du Chien aquifer.

Recharge to the upper carbonate aquifer is primarily by direct infiltration of rainfall. Recharge to the St. Peter is primarily from vertical infiltration from the overlying upper carbonate aquifer, particularly near the erosional edge of these units where they are transected by the erosional valleys that cut through these strata, and where the Decorah-Platteville-Glenwood confining unit has been removed by erosion. The groundwater flow patterns in the aquifers are controlled by the valleys and gorges that comprise the major groundwater discharge areas, and also by pumping of water wells.

The upper carbonate aquifer is heavily cut by streams and rivers which drains this aquifer quite effectively, and seeps and springs are common at the erosional edge of this unit. Groundwater usage from this upper carbonate aquifer is primarily in the upland areas of Olmsted County (the southern half of the county) and the Prairie du Chien Group of central Winona County, and wells are found to be more productive where they intersect fractures, joints or solution channels. These aquifers are reported to have relatively high overall permeability due to karst features, with well yields as high as 200 to more than 1,000 gallons per minute, but potential yields are highly variable due to the variations in karst features. Movement of water in the till is intergranular and could potentially supply a well.

In much of the region, the drift deposits overlying the upper carbonate aquifer are either absent or too thin to act as a protective barrier against the migration of surface contamination down into the aquifer. There is evidence of nitrate contamination in the upper carbonate aquifer in parts of each county.

HYDROGEOLOGICAL CONDITIONS IN THE PROJECT AREA

The existing rail line in Olmsted County crosses five distinct areas where the uppermost bedrock comprises different, generalized bedrock geologic settings. The eastern end of the line occurs in a valley where the bedrock comprises primarily non-carbonate rocks, including the St. Peter Sandstone and Decorah Shale. Dolomites of the Prairie du Chien Group occur locally in this area also. To the west of this segment, the line crosses a broad belt of the carbonate bedrock strata comprising the upper carbonate aquifer. This is the bedrock sequence where most of the karst conditions are focused within the county. Multiple sinkholes occur in these units to the south of the existing rail line. Farther to the west, the existing line then cuts through two symmetrical belts of Decorah and St. Peter as the line drops down into and up out of the valley occupied by the city of Rochester, with a broad belt of the Prairie du Chien dolomites in the floor of the valley occupied by the city. Then, at the western end of the line, the bedrock beneath the uplands comprises once again the upper carbonate aquifer rocks.

The proposed rail bypass line south of Rochester crosses a different series of bedrock strata for most of its length than the existing rail line. Except for highly localized areas where the bypass route crosses narrow stream valleys where the Decorah is exposed, the entire line is in areas where the bedrock comprises the upper carbonate aquifer rocks. It is this bedrock type that exhibits the most highly developed karst setting in the county.

Thus, while the existing line transects the upper carbonate aquifer for approximately one fifth of its length, the bypass route is in the upper carbonate aquifer for nearly its entire length.

The dip of the bedrock strata is typically at a low angle (approximately one fifth of a degree) to the southwestward within the county, with local variations due to minor folding and faulting.

The carbonate bedrock strata (limestone and dolomite) within the Paleozoic rocks have been subject to dissolution by long term chemical weathering by a weak carbonic acid formed by the reaction between the groundwater and the carbon dioxide from the biologic activity in the soil and air. This dissolution has caused the karst conditions, with some localized areas more heavily affected than others.

Retreat of the Galena and Platteville plateaus in Winona County has exposed the Oneota Dolomite to erosion. Its escarpment is being eroded by stream drainage and eventually will also retreat toward the southwest. The corrosive action of slightly acid groundwater in carbonate bedrock enlarges the joints and dissolves cavities in the bedrock, resulting in karst conditions. In striking contrast to Olmsted County to the west, there are very few sinkholes in the Galena Group rocks. Rather, most of the karst conditions in Winona County occur in the dolomites of the Prairie du Chien Group.

The proposed railyard lies across the outcrop belt of one bedrock stratum for its entire length, the bedrock strata assigned to the upper carbonate aquifer rocks of the Prairie du Chien. This unit exhibits the highest potential yeilds for groundwater and the highest percentage of sinkholes for the entire county with the higher yield areas showing the highest sinkhole presence.

POTENTIAL GEOLOGIC CONCERNS RELATED TO RAIL LINE REROUTING-ROCHESTER AND LEWISTON

Karst

The proposed Rochester bypass route and the new railyard near Lewiston transect a significant karst terrain. This karst terrain is known to be active, with sinkholes having formed within the last several years in Olmsted County where Rochester is located and during a recent (1984) one-year study in Winona County where Lewiston is located. The appearance of the existing sinkholes, with significant open voids beneath them confirms that sinkhole formation is active and ongoing. Construction and operation of a railroad in these areas would entail a significant risk of catastrophic collapse. This is due to the presence of limestone bedrock strata within the shallow subsurface that have been subject to solutioning by groundwater over long periods of geologic time. This solutioning has resulted in the presence of caves, enlarged joints, and voids within the bedrock.

Sinkhole Formation

The first step in sinkhole formation is the dissolving of carbonate rocks (limestone and dolomite) by percolating groundwater, to the point where substantial air or water filled voids occurs in the bedrock. These voids, in the form of caves or solution-enlarged joints and fractures take many centuries to form. Where the caves or voids occur well below the upper surface of the bedrock and therefore have a relatively thick roof rock beam, they may be considered stable.

Infiltration of rainfall may carry soil particles downward into the cave or void. Even if the bedrock voids are relatively small, they can accommodate a substantial volume of soil if groundwater is flowing through the cave in the rock, as the soil will be carried off through the subsurface fracture network.

As the soil trickles down into the cave, it may leave a sizable void within the soil overburden layer, particularly in clay and silt type soils that have a certain amount of cohesion.. If the soil layer is thick enough, it can bridge over a substantial void. A diagram of this type of situation is shown in Figure 4, excerpted from Building on Sinkholes, (Sowers, G.F., 1996).

This situation presents the most hazardous condition that one can have in trying to build an engineered structure in an area of karst: hidden soil voids of substantial volume that could collapse at any time. The hazard is increased where the engineered structure is heavily loaded, involves vibration, or may involve the release of large volumes of water. Under these conditions, there is a significant risk of catastrophic failure of the structure. Extraordinary engineering efforts would be required to design a reduced risk facility.

Evidence for the possible presence of hidden subsurface soil voids in a karst area include the following:

1. Active, on-going formation of sinkholes in historical times. This indicates that even though cave formation within the bedrock may be taking place only very slowly, the trickling of soil downward into these caves and voids is actively taking place.
2. The presence of substantial air-filled voids in the soil beneath sinkholes that have already formed. This indicates two key facts, first, that the soil roof beam over the cave, although partially collapsed, is still at least partially bridging over. It confirms that the soil is capable of bridging over a substantial void. Secondly, it indicates that not only the volume of soil that once occupied the sinkhole has disappeared underground, but an additional significant hidden volume as well (the volume of the bridged over soil void beneath the bottom of the sinkhole cone).
3. The presence of steep, scarified sinkhole walls that are devoid of vegetation and showing evidence of active erosion, as opposed to relatively flat, gradual slopes down into a gentle depression. These indicate that subsidence into the underlying void has been rapid and recent, such that the sidewalls of the pit have not had time to be washed into the sinkhole and be revegetated.
4. Sagging of localized areas of terrain into closed depressions with no external drainage. These may indicate the gradual surface subsidence of a soil roof beam that is sagging into a void. Or, they could also indicate areas of subsidence merely due to loss of soil material down into the bedrock void system, where the soil is being transported underground. These localized areas of sagging of the soil roof beam over a void can be particularly problematic, because the sag in the terrain accelerates the infiltration of water into this area, accelerating the potential collapse.

5. Evidence of significant water flow out of the bottoms of sinkholes. This indicates that relatively large amounts of soil are being transported into the subsurface and being carried off by flowing water.

Evidence of all five of these phenomena occur in the karst area along the proposed Rochester rail bypass route. The sinkhole shown in Figure 5 was reported to have formed overnight in the farm field , within the last several years. This sinkhole is located within the sinkhole swarm in and around Section 21, T.106 N, R.12 that is crossed by the proposed bypass line.

Figure 6 shows the presence of a substantial void (over three feet deep), as discussed in item 2, above, in the soil beneath a sinkhole that is within the same cluster of sinkholes. Also visible in this figure are the very steep, scarified sinkhole walls, as discussed in item 3. Figure 7 shows another sinkhole in the same area that comprises a closed ground surface depression with no external drainage, as discussed in item 4, where the overburden soil is either sagging into a subsurface void or where soils are being undermined by subsurface groundwater flow.

Figure 8 shows streamlines in sand at the bottom of a sinkhole, indicating that a significant amount of water flows through the sinkhole and out the bottom, and that groundwater flow in the bedrock is able to transport and accommodate large volumes of soil material. Thus, there is room for additional soil displacement down into the rock, and the sinkhole is actively growing. The formation of new sinkholes in the area may be readily anticipated, due to the apparent carrying capacity of subsurface water flow and its ability to undermine soil bridges over bedrock cavities.

Thus, the major types of evidence which would indicate the presence of active and ongoing formation of sinkholes are all present in the immediate vicinity of the proposed Rochester rail bypass route.

The absence of these features along the remainder of the proposed bypass route does not indicate that the potential consequences of karst are limited to only the area that currently shows evidence of multiple sinkholes at the surface. This conclusion is based on the fact that the bulk of the known sinkholes in this area have formed where the soil overburden is very thin (less than approximately 10 feet). However, a small number of sinkholes exist where the soil overburden is more than ten feet thick.

There are two potential explanations for this apparent relationship between overburden thickness and frequency of occurrence of sinkholes. The first is that the areas with relatively thin overburden soils experienced a greater amount of infiltration of rainwater, causing a greater amount of dissolution of the carbonate rocks below. The second is that there are an equal number of caves and bedrock voids beneath the areas with thicker overburden soils, but the thicker overburden bridges over the voids better. Where the overburden is thicker, the surficial soils can bridge over larger voids. This latter case would involve a tremendous risk to a heavily loaded structure, such as a rail line, because the equilibrium under which the voids exist would be disrupted by the addition of significant additional loads. In other words, a train could precipitate the collapse of an existing, currently stable void. It is the risk of this latter possibility that presents a difficult subsurface exploration and design challenge for the construction of large engineered structures such as a rail line in karst areas.

Another aspect of sinkhole formation that needs to be considered for this project is whether there will be changes in the elevation of the water table, either a rise or fall in the future. This is because lowering the water table increases the gradients in the vicinity of openings in the rock surface and promotes soil erosion. In addition, the effective stress in the soil increases as the buoyant effect of the water is lost, which leads to local soil failures and the tendency for soil to break loose at soil water interfaces. Repeated fluctuations of the water level from above the rock-soil interface to below it particularly aggravates sinkhole development.

Increased usage of groundwater in the county would lead to lowering of the water table. Regional lowering of the water table, as well as local water usage from wells locally lowering the water table would accelerate the rate of sinkhole formation.

An investigation of karst conditions led to publication of a map of sinkholes and sinkhole probability in Olmsted County (Alexander, E.C., Jr., and Maki, G.L., 1988, sheet 7 of the Geologic Atlas of Olmsted County). The criteria for mapping different levels of probability are as follows:

No Probability: In areas where no carbonate rock exists due to erosion in deep valleys. This is the only area in Olmsted County where sinkholes are not likely to form.

Low Probability: In areas where no sinkholes were observed and there was more than 50 feet of cover over the bedrock and in areas of steep slopes and bluffs.

Low to Moderate Probability: In areas where the bedrock surface is covered by a thin layer of drift and the sinkholes are very widespread, with the average sinkhole density of less than 1 per square mile (low) with only a few sinkhole clusters (moderate).

Moderate to High Probability: In areas where the average sinkhole density is 1 to 5 per square mile and the sinkholes occur in clusters of three or more, and the overburden soils are underlain by any of the carbonate bedrock units. These areas are stated to be a significant engineering concern, especially for large facilities. The proposed bypass route crosses through two major areas with this classification.

High Probability: In areas where the average sinkhole density is 5 to 20 per square mile and the sinkholes are a common feature in the area, and the soils are underlain by any of the carbonate bedrock units. These areas are highly sensitive to fluctuations in groundwater, weight of structures built on the surface or changes in hydraulic conditions. The highlands near steep sloped valleys are a highly susceptible area due to the increased hydraulic gradient in this area.

Karst Topography: In areas where the average sinkhole density is 20 to hundreds per square mile and are a dominant feature. All of the precipitation infiltrates or flows into the karst features. These features are a major concern for any construction in the area. This high density of sinkholes exclusively occurs in areas underlain by bedrock strata assigned to upper portion of the Galena group. The proposed rail bypass route directly crosses one of these karst terrain areas.

The areas of Olmsted County that are classified as having moderate to high probability and karst topography are relatively limited. In other words, the greatest risk of sinkhole collapse occurs in some relatively small areas. These areas are restricted primarily to locations where the Stewartville and the upper portion Prosser Limestone strata comprise the uppermost bedrock, and where the soil overburden is relatively thin. The existing rail line can be seen to occur entirely within areas that are classified as low to moderate probability for sinkhole formation. The proposed bypass route crosses a significant area of low to moderate probability also, but it also transects several significant areas classified as having both moderate to high probability of sinkhole formation and one area of karst terrain.

The area of the proposed railyard within Winona County has a similar ranking for sinkhole probability, based on the Geologic Atlas Winona County, Plate 3 (Balaban, N.H. and Olsen B. M. 1984). The area of highest probability is located on the uplands in the central portion of the county. In the western part of Winona County, large clusters of sinkholes have formed in the Prairie du Chien aquifer where the water table is relatively close to the ground surface. Fluctuations in the water table in this area probably exacerbates sinkhole development, overriding the effect that the calcareous till has in diminishing the rate that acidic groundwater is likely to dissolve the rock to form voids in the bedrock. In the eastern part of the high-probability region, sinkholes have formed primarily in areas of noncalcareous, thin tills and thicker residium. These surficial sediments probably provide conditions that promote continued carbonate dissolution and sinkhole collapse even though deeply incised valleys and the very deep water table should inhibit sinkhole formation. Areas where the sandstone member of the Shakopee overlies the Oneota Dolomite are the most susceptible to sinkhole formation. It apprears that joints in the non calcareous sandstone collect acid water without neutralizing it, and direct the water into the Oneota where it dissolves the bedrock. The surficial sediments, topography, and water table are secondary controls that vary in significance relative to the likelihood of new sinkhole formation throughout the county.

Although the ranking system of low, moderate, and high probability of sinkhole formation plus karst terrain carries the implication of lower risk to higher, these criteria must be used with some caution, because they are based on the present appearance of the ground surface. In other words, the areas with the most sinkholes now are deduced to have the greatest likelihood of sinkhole formation in the future. T*his is true only under current structural loading conditions.* Most sinkholes form at the surface where the soil overburden is relatively thin, and the soils are not able to bridge over large cavities. In thicker soils, similar or substantially larger cavities may form in the subsurface and be able to remain bridged over for a long period of time. If substantial additional structural load is added to the roof beams or their equilibrium is otherwise disturbed, they could collapse.

The conclusion that must be reached is that the risk of collapse of hidden subsurface soil voids is likely as severe in areas classified as "low to moderate" probability as they are in the "high" probability areas, where the lower to moderate ranking is due to the presence of a thicker overburden layer. In other words, the absence of sinkholes in areas of carbonate bedrock with thicker overburden soils may pose even a higher risk to a project such as a railroad than the areas designated as karst or high risk.

A review was performed of the USGS 7 ½ minute topographic maps for the area of the existing rail line and proposed Rochester bypass in Olmsted County, plus the area of the proposed railyard and surrounding area in Winona County, to confirm the data provided on the karst map of the county. This review revealed the presence of numerous surface depressions that have no outlet, as well as multiple springs characteristic of karst conditions.

The first hazard to engineered surface structures from these voids is that hidden caves within the bedrock might collapse. Although this possibility is not highly likely, due to the significant strengths of most rock strata, it is still possible. Catastrophic collapse of the roof of a hidden cave could occur if the roof beam of the cave were thin enough or of inadequate strength to bridge over the cave under the loading conditions imposed by a loaded and moving train. Reducing the risk of collapse of a hidden cave would entail a significant amount of prior subsurface investigation, preferably with a combination of geophysics and geotechnical drilling.

A second, more serious problem than the simple collapse of a hidden cave is posed by voids in the overburden soil formed by groundwater moving through caves or solution enlarged joints in the bedrock, undermining the soil overburden. In places, the soil overburden collapses into the bedrockcave or joints, forming a dome shaped void, or cavity in the soil. Where the soil has already collapsed to form a sinkhole at the ground surface, the seriousness of this problem is much reduced, and the cratered terrain can be remediated with engineering measures, such as backfilling with crushed rock, at some cost. But the greatest risk is that, given the right conditions, the soil may bridge over the bedrock voids, resulting in hidden and relatively unpredictable hazards. It is where the voids have not yet collapsed that the enormous risks of catastrophic failure exist. The time frame for collapse of such a void is relatively unpredictable: it may collapse today, or it may collapse twenty years from today. This condition is illustrated on Figure 4, Sketches a and d, excerpted from Building on Sinkholes (Sowers, G.F., 1996).

Building heavily loaded structures over an area of potential voids significantly increases the risk of collapse. Vibrating the structure, as with machinery, increases the risk by introduction of dynamic loading, as does changing the groundwater table level, as might happen in the event of a tank leak or spill. Since these exacerbating conditions would be associated with construction of a railroad, the risks to collapse of voids in this area would increase if a railroad were to be constructed in this area. In other words, the collapse would most likely occur when a train is crossing a void.

Thus, in areas where the line and railyard would be built at grade or on a fill, the possible existence of sizable dome shaped cavities in the soil presents a substantial risk of catastrophic collapse of the soil roof beam. In segments of the line that would be constructed in excavations cut down to or into the top of bedrock, these soil cavities would be removed, and this risk would be removed. In the cut sections, the risks would entail potential collapse of hidden, thin-roofed bedrock caves or difficulties in backfilling any sizable bedrock caves that are exposed in the cuts.

RISK OF POTENTIAL SINKHOLE COLLAPSE ALONG THE PROPOSED ROCHESTER BYPASS ROUTE AND EXISTING ROUTE

The existing route through Rochester occurs over different geologic strata than those that occur beneath much of the bypass route. The strata along the existing route through Rochester are obviously much less susceptible to karst formation, evidenced by the lack of sinkholes along nearly the entire route. The risk that hidden voids occur within the soil overburden along the existing route is substantially less than along the proposed bypass. This conclusion is based on two primary facts: known sinkholes are very scarce along the existing Rochester route but are very common in the general area of portions of the bypass route, and secondly, the railroad has operated along the existing line for many decades, and if voids in the soil had occurred, they likely would have been already collapsed by the loading and vibration from the operation of the railroad. In other words, the operation of the railroad has already provided an exploratory test for potential sinkholes along the existing line.

The fact that sinkholes are common along the proposed bypass route and rare along the existing route is due in large part to the fact that the bedrock strata beneath the proposed alternate route are different from the existing Rochester route, with the proposed bypass route having a significant amount of solutioning of the bedrock.

Geotechnical engineering measures to mitigate the risk of catastrophic collapse along the proposed bypass route in the future would likely include a detailed seismic shear wave geophysical survey of the portions of the line passing through the active karst area to attempt to define likely locations of voids in the soil and caves in the bedrock, a drilling and sampling program to confirm the results of the geophysics, dynamic compaction of the soils and bedrock along the proposed route to intentionally collapse voids in the soil or caves in the bedrock before construction, backfilling of existing sinkholes, and monitoring for subsidence in the future for the life of the project. The combined costs for these measures would be in the range of millions of dollars.

RISK OF POTENTIAL SINKHOLE COLLAPSE IN THE AREA OF THE PROPOSED LEWISTON RAILYARD

The proposed railyard near Lewiston in Winona County occurs under different geological conditions than those that occur beneath the rail line through Rochester in Olmsted County. The uppermost bedrock geologic strata along the existing route through Rochester and those in the area of the railyard are both assigned to the Prairie du Chien Group, and both are carbonate strata susceptible to solutioning by groundwater that can lead to karst conditions. However, beneath Rochester these strata are either less susceptible to karst formation, or are buried so deeply beneath the unconsolidated overburden that the effects of the karst only rarely reach the ground surface, evidenced by the lack of sinkholes along nearly the entire route of the existing line through Rochester. The top of bedrock beneath Rochester is 150 to 200 feet below ground surface, while in the railyard the bedrock occurs at depths of approximately 20-35 feet or less.

Thus, in the area of the proposed railyard, known sinkholes are very common, because the thin overburden soils are not able to bridge over caves and solution-enlarged joints within the bedrock as well as the thick soils in Rochester.

The engineering mitigation measure most likely to overcome the construction challenges imposed by the karst conditions in the area of the proposed railyard is relocation of the facility away from the high-risk area. Placement of the railyard on the area south and west of the town of Utica, in the area where the uppermost bedrock comprises the St. Peter Sandstone and the Decorah Shale would vastly diminish the potential for catastrophic formation of sinkholes that could possibly cause derailment. Excavation to bedrock over such a large area (multiple square acres) would likely be so costly as to not be feasible.

In the current proposed location of the railyard, geotechnical engineering measures to mitigate the risk of catastrophic collapse in the future would likely include a detailed seismic shear wave geophysical survey of the portions of the proposed yard to attempt to define likely locations of voids in the soil and caves in the bedrock, a drilling and sampling program to confirm the results of the geophysics, dynamic compaction of the soils and bedrock along the rail lines within the yard to intentionally collapse voids in the soil or caves in the bedrock before construction, backfilling of existing sinkholes, and monitoring for subsidence in the future for the life of the project. The combined costs for these measures would be in the range of millions of dollars.

POTENTIAL FOR GROUNDWATER POLLUTION DUE TO SURFACE SPILLS AT ROCHESTER AND LEWISTON

The primary area of risk of causing significant groundwater contamination from operation of a rail line or railyard is via catastrophic release, such as rupturing of a tanker car (due to collision, derailment, etc.). As discussed above, the risks of such a release are higher in areas of significant karst because of the potential for catastrophic collapse of a subsurface cavity while a train is crossing it. Therefore, risks of significant contamination to groundwater (as well as risks of contamination of surface water and risk of direct exposure to humans,) are much greater along the proposed Rochester bypass route and railyard location than along the existing route through Rochester. Possible human health risk exposure would be through ingestion of contaminated groundwater as well as inhalation and dermal contact pathways for emergency workers, railroad employees, bystanders, and neighbors.

In addition, however, there is also an issue of potential groundwater contamination from releases due to accidents or occurrences not related to derailments caused by formation of sinkholes in karst terrain: collision, for example. In general, the risks of potential groundwater contamination are high along the proposed Rochester bypass and in the area of the proposed Lewiston railyard, and significantly lower along the existing line through Rochester.

GROUNDWATER POLLUTION ALONG THE PROPOSED ROCHESTER BYPASS ROUTE

In order to evaluate the potential for groundwater contamination from any releases along both the existing route and the proposed bypass route in Olmsted County, both alignments were plotted on the map titled Sensitivity of the Groundwater System to Pollution in Olmsted County (Olsem, B.M., and Hobbs, H.C., 1988, sheet 6 of the Geologic Atlas of Olmsted County). As indicated on that map, the suseptibility of a particular area for groundwater contamination to occur has been assigned to several different levels of concern, labeled "Sensitivity Ratings". These ratings are defined as follows:

Very High: Contaminants will almost certainly reach the water table in hours to months. The rapid vertical migration of contaminants is related to the presence of karsted limestone or dolomite bedrock, in areas where overburden soils that could retard the migration of contaminants are thin to absent. In this geologic setting, contaminant migration could be on the order of miles per day, rather than feet or inches per day typical of other geologic settings. The end result is that there would be little time for mitigating measures to be implemented effectively to prevent the contaminants from reaching the water table or from traveling large distances. These areas typically correlate with areas of shallow water table, thin to absent overburden soils, porous and permeable overburden soils, and karst conditions, due to the presence of open subsurface voids, including sinkholes. In the case of a sudden release, such as large accidental spill related to train derailment, this geologic setting is much worse than any of the other ratings, even the "high" rating. This is because emergency spill containment measures, if implemented quickly, would likely be able to control most (or at least some) of the spill in any of the other geologic settings, based on even slight retardation that could hold some of the contaminants back for even a couple of hours. This would not be true in the "Very High" sensitivity areas, where a tanker car spill would likely disappear into the ground in a matter of minutes to a few hours.

High: Contaminants will probably reach the water table in weeks to years; little natural protection exists to retard the vertical movement of liquids. These areas are characterized by karsted bedrock, but with the presence of some shale interbeds, sandstones, and bouldery gravel terrace deposits. Much of the central part of the City of Rochester occurs in this high sensitivity area, because the principal drinking water aquifer (comprising the Prairie du Chien Dolomite and the Jordan Sandstone) occurs under unconfined conditions, and the water table is fairly shallow. Therefore contamination could reach the water table and move relatively rapidly.

High - Moderate: Contaminants will reach the water table in several years to about a decade. These conditions occur where glacial till deposits are five to fifty feet thick, where colluvium (soils derived from weathering of the bedrock), and where groundwater may be perched on bedrock.

Moderate, Low-Modereate, and Low: For purpose of this investigation, these sensitivity ratings are grouped together because of the long travel times (a decade or more) that would allow time for cleanup of accidental spills before the groundwater is impacted. This level of sensitivity means that the geology in the area exhibits significant potential to impede the infiltration such as a confining layer (i.e. the Decorah, Platteville-Glenwood sequence) present over the aquifer.
A number of segments of the proposed bypass route traverse areas rated as Very High sensitivity of the groundwater system to pollution. This includes a significant portion of the line (approximately five miles long) southeast of the City of Rochester, in an area of karst terrain with thin to absent soil overburden. In addition to this major area, the bypass route crosses five other areas ranked as Very High sensitivity, ranging from less than a quarter of a mile long to over two miles long. Most of the remainder of the line is rated as High – Moderate or lower, while several short segments are ranked as High.

The existing rail line traverses two segments of terrain rated as Very High sensitivity, and each of these are less than one quarter of a mile long.

Because of the serious differential between the Very High sensitivity ranking (where efforts to mitigate a catastrophic spill before it reaches the water table would probably not have time to be implemented,) and all of the other categories, it is apparent that the bypass route poses much greater risks to human health and the environment than the existing route. Likewise, the likely costs associated with a cleanup of a spill would be many times higher along the bypass route. This cost differential would be due to the fact that although both cases would require emergency spill cleanup at and near the surface, a spill along the sensetive areas of the bypass route would likely include groundwater cleanup of a plume in the aquifer that would likely require decades and many millions of dollars to remediate. In addition, it is likely that sources of water supply would be impacted, with risks to human health and also costs of providing alternative water supplies.

SUSCEPTIBILITY TO GROUNDWATER POLLUTION, PROPOSED RAILYARD

In order to evaluate the potential for groundwater contamination from any releases in the area of the proposed railyard, its location was plotted on the map titled Susceptibility of the Ground-water System to Pollution in Winona County (Kanivetsky, R., 1984, sheet 6 of the Geologic Atlas of Winona County). As indicated on that map, the susceptibility of this entire area for groundwater contamination to occur has been assigned a high level of concern. This rating is defined as an area having the most potential for sinkhole development anywhere in the county. This is the highest rating for the susceptibility of the groundwater system for pollution in this county and is similar to the very high rating in Olmsted County. Sinkholes are numerous and occur regardless of the composition of the unconsolidated deposits. The Prarie du Chien-Jordan aquifer is under unconfined ground-water conditions and its water table is higher than elsewhere in the county. As a result, contaminants that reach the Prairie du Chein may move rapidly into the ground-water system through interconnected sinkholes, cracks, and countless solution cavities. The Prairie du Chien Group is a major aquifer in the western half of the region, and many older wells were completed in it. Like the area of the proposed bypass at Rochester, if a spill were to occur in this highly susceptible area, cleanup of a plume would likely require decades and millions of dollars to remediate. In addition, it is likely that sources of water supply would be impacted, with risks to human health and also costs of providing alternative water supplies.

There are no known practical engineering mitigation measures that would likely reduce the risks of groundwater contamination along the bypass or in the area of the railyard to the same level of risk currently incurred along the existing line. Construction of extensive spill containment and liner systems along multiple miles of track through the sensitive areas might be physically possible but would be costly.

CHANGES IN GROUNDWATER FLOW PATTERN

The construction of a rail line along the proposed bypass route and near Lewiston, like many other types of civil earthworks could entail diversion of surface water. Such engineered features might include construction of embankments, placement of culverts, installation of drainage diversion ditches, or excavations. Under certain conditions, such features can locally impact surface water bodies, springs, and wetlands.

Embankments constructed across natural watercourses can act basically like small dams, diverting water around wetlands. Culvert placement and stormwater drainage ditch designs that suit the best engineering design may not accommodate preservation of surface water flow into wetlands. And major excavations, particularly cut sections along linear engineered structures such as railroads may be excavated down into the water table, or perched water table, interrupting their natural groundwater flow pattern. Since such an excavation would then become the local groundwater discharge point, the natural flow pattern feeding water supply wells, springs, seeps, and wetlands would be interrupted, and they could potentially dry up.

Along the existing rail line, such interruptions have already taken place decades ago, and no further impacts would be likely.

Construction along the proposed bypass route and near Lewiston would generate a new potential set of impacts. Areas that need to be evaluated for potential impacts that could be anticipated due to construction of embankments along the rail bypass and near Lewiston would include existing wetlands on or adjacent to the route. Engineering design of the embankments would then need to incorporate features, such as appropriately placed culverts, to eliminate these impacts.

In those cases where deep cut excavations would interrupt the water table, engineering measures to mitigate impacts on springs, seeps, and wetlands would be unlikely to be effective. In other words, once the natural flow pattern is diverted to a new major, linear groundwater discharge zone such as a railroad cut, it would be highly problematic to maintain the existing groundwater flow pattern in the downgradient direction.

ENGINEERING MEASURES TO MITIGATE IMPACT OF KARST ON LARGE STRUCTURES

There are a number of engineering measures that could be employed to reduce the risks of potential catastrophic collapse of large structures due to karst. These include:

- Relocate the proposed structure to areas with lower risk
- Change the grade of the railroad by excavating off the soil in karst areas, to place the rail line on or within cuts in the bedrock.
- Perform specifically designed geophysical surveys to identify subsurface locations with potential voids
- Perform subsurface exploratory drilling to confirm the results of the geophysics
- Intentionally collapse subsurface voids within the design footprint of the project before construction
- Attempt to grout suspected problem areas
- Overexcavate and backfill, with a specifically designed backfill material, existing sinkholes or intentionally collapsed voids
- Monitor for subsidence and for potential subsurface soil cavity formation for the life of the project.

The following discussion addresses each of these potential measures.

Depending on the level of need of an owner to locate a particular facility at an exact location, the most practical way to avoid or reduce risk of catastrophic collapse is to site the facility in an area where the karst conditions are less severe. The first level of screening in the siting of a major facility such as a railroad (or any other major industrial facility, such as a power plant or sanitary landfill) should include an evaluation of karst conditions. Avoiding areas with a high probability of sinkhole formation would go a long way toward reducing risks that would then render a project potentially feasible.

Changing the grade of the railroad by excavating off the soil in karst areas, to place the rail line on or within cuts in the bedrock would allow the most serious potential collapse problems (of voids in the soil overburden) to be removed. Exposing the bedrock surface would expose evidence of caves within the bedrock as well, allowing them to be remediated by backfilling with free draining structural backfill. The design of the backfill would need to be carefully engineered to prevent further losses of fine particulates into the bedrock voids in the future.

Very specific types of geophysical surveys can be performed in the area of a proposed structure to attempt to identify possible uncollapsed subsurface voids, in both soil and bedrock. The most promising of these techniques is shallow seismic reflection of surface shear waves. This involves detonating small explosive charges in shallow boreholes, and tracking the seismic shear waves in lines of geophones. The key to the analysis of this innovative method is computer interpretation of the seismic signals by a qualified specialist. Where this technique has been applied to investigate siting of a power plant in a karst area of southern Alabama, the cost of even a relatively small investigation was over one million dollars. Since the proposed rail bypass line is many miles long, the proportional cost can be projected to be in the range of millions of dollars.

Geotechnical drilling would be required to confirm the results of the geophysical survey, since the geophysics are considered to be somewhat experimental. We would not recommend using a drilling program by itself without the geophysics to investigate karst, because the borings would have to be so closely spaced to confirm that even small voids do not exist that the cost would be outrageous. For example, if the sudden formation of a sinkhole similar to that shown in Figure 3 would be sufficient to derail a train, and if the sinkhole in Figure 3 were about 20 feet in diameter, a drilling program would have to include borings on less than twenty foot centers. The cost of the drilling program would be on the order of many millions of dollars.

Given the relatively thin overburden along the proposed rail bypass, it would likely be possible to deliberately collapse any possible voids along the rail line before construction. This would be done by a technique called dynamic compaction, where a heavy disk of steel (several tons) is raised up in the air with a crane to a height of approximately 15 feet and then released. This technique would likely collapse any existing voids to a depth of approximately 25 feet below ground surface. One could either perform the dynamic compaction along the entire route at a cost of millions dollars), or use the technique where the geophysical survey indicates that subsurface voids are most likely, which would reduce the cost.

After the dynamic compaction effort would be completed, grouting could be attempted to prevent the future raveling of subsurface soils into bedrock voids. The results and effectiveness of grouting in karst conditions would be considered uncertain, due to the complex pathways the grout may take in such a jointed bedrock system.. In other words, it is difficult to tell where exactly the grout is ending up and whether it is accomplishing its intended purpose.
Existing sinkholes along the proposed route should be overexcavated and backfilled with a free draining crushed rock backfill designed to be free draining and prevent the further infiltration of fine soil particulates.

Because all of these mitigation techniques entail some level of uncertainty, it would be prudent to monitor the line for subsidence after it is built. A well designed monitoring system may be able to detect gradual subsidence that would likely precede catastrophic collapse, so that further collapse prevention methods could be employed.

REGIONAL GEOLOGIC SETTING-SKYLINE

From a hydrogeological perspective, the primary concern regarding the proposed bypass route south of the City of Mankato relates to geotechnical issues related to placement of the line at the toe of the bluff immediately to the west of the Skyline Subdivision at the western edge of the City of Mankato.

The geologic setting at this locality is characterized by a thick section of glacial drift, overlying Ordovician age bedrock (sandstones, dolomites, and shales). Based on the published geologic information in Vogel, Paul, and others, 1991 (*Geologic Atlas Of Blue Earth County, Minnesota*), the glacial drift at this locality is relatively thick, such that concerns for slope failure are within the drift. At this locality, the drift is composed mainly of glacial till, which is characterized by a matrix of sand, silt, and clay with scattered pebbles, cobbles, and some boulders which could range in thickness from 150 feet to over 300 feet.

At the Skyline location, the proposed alignment is between the Blue Earth River and a 200-foot high bluff. Homes in Skyline line the crest of the bluff. Figure 9 is a view of this bluff, seen from the south, where a stream channel has eroded a side valley transecting the bluff from east to west. This photograph thus provides an "edge-on" view of the bluff, giving an idea of its slope angle.

The western face of this bluff is apparently a cutbank of the Blue Earth River, formed within a thick section of glacial drift. The concern for placement of a rail line at the toe of this bluff arises from the fact that there is little room between the river and the bluff to place a rail line without excavating a steep cut at the toe of this slope. Since the slope comprises a natural cutbank that has been subject to mass wastage and erosion, its current configuration is in state approaching natural equilibrium. Excavating a cut at the toe of this bluff would disrupt this equilibrium, and could precipitate a slope failure on a massive scale.
Within the immediate vicinity of the site in question, several slope failures are visible within the glacial drift. Figure 10 shows a relatively minor slope failure on the ski slopes within the glacial drift bluffs immediately south of the Skyline bluff. It appears that this slope failure may be related to steepening of the natural slopes where the relatively less steep ski runs may have been excavated. This example demonstrates a potential hazard of steepening slopes in this geologic unit.

Figure 11 shows another slope failure along a well-thought out and planned, engineered slope that is part of a highway cut south of the Skyline bluff area. This example is included to demonstrate that even where slopes are calculated to likely be stable, according to reasonable engineering practice, slope failures can occur if the slopes are steepened even just slightly too much, or if the geologic characteristics of a particular geologic formation (particularly inherent inhomogeneities or groundwater occurrence) render it susceptible to relatively unpredictable slope stability characteristics.

Once again, this example provides a relatively small scale example of potentially much larger problems on the bluff face at Skyline.

Geotechnical engineering measures to mitigate the effects of cutting at the toe of the Skyline Bluff are likely to be difficult and costly. These would likely involve a substantial retaining wall and tieback system, dewatering to control flow from any springs that might form in the excavation, revegetation of slopes above the retaining wall, and monitoring for the lifetime of the project. A catastrophic failure of this engineered system could possibly result in derailment of a train into the Blue Earth River, with serious potential human and environmental consequences.

An alternative approach would be to cut the slope back at an angle low enough to not be likely to precipitate a major slope failure, and to accommodate any material that did come down in minor slope failures. This would likely require a massive amount of excavation and the removal of homes from the crest of the Skyline bluff.

In either case, the costs of mitigating this problem would be substantial.

GEOLOGY AND GEOLOGIC CONCERNS REGARDING THE PIERRE SHALE

Construction in and around the outcrop area of this shale unit has been a concern for many decades. Studies on the landslide potential of the Pierre Shale have been conducted for the South Dakota Department of Transportation and the Federal Highway Administration both in stable and unstable areas to develop methods for delineating unstable areas prior to construction as documented in Landslides in the Pierre Shale in Central South Dakota-Executive Summary Report by J. Scully, 1975>. As noted by Scully, the main and overall determining factor on the stability of shale is the absence or presence of water. Flow of water into and through shale is not uniform and can cause differences in the stability of adjacent slopes. There are many factors that influence the flow of water in the shale (i.e whether the physical and/or chemical makeup of the shale will result in the storage, flow through, or retardation of water flow). Vertical flow is controlled by joints, cracks, and faults but is also related the chemical properties of the unit. Continuous vertical flow is most likely in the calcareous, siliceous, and non-bentonitic shale members. Tables 1 and 2 from the report by Scully summarize the factors that influence the water entry into and the flow through the Pierre Shale.

The Pierre is mainly a body of fine-grained rocks that were deposited as muddy sediments in a marine (ocean) -environment that reached the east and central Dakotas. The sediments that comprise this formation were derived from the weathering and erosion of older rocks. After deposition, the sediments were consolidated and lithified to form rock. The Pierre shale consists of approximately 200 meters of marine shale with about 50 percent clay minerals, 25 percent quartz, and five percent each plagioclase, calcite, and dolomite, and about one percent each of cristobalite, potassium-feldspar, and organic matter. Pyrite, zeolite, and siderite also may be present (Minerology and Chemical Composition of the Pierre Shale and Equivalent Rocks, L. G. Schultz, 1981). The Pierre shale is made up of seven memebers, mostly bentonitic shales with occasional calcareous and siliceous shale layers. A detailed summary of the stratigraphy of the Pierre shale formation is included in Table 3.

The largest slides within the Pierre shale occur within the Mobridge Member and the siliceous facies of the DeGrey Member, in which most of the vertical flow occurs, as infiltration of rain water, and they overlie deeper bentonitic layers. Smaller slides occur in the Virgin Creek, Verendrye, DeGrey Members (shale and bentonite facies) and the upper part of the Gregory Member, which is partially bentonitic shale layered with a varying number of bentonitic interbeds. The greatest potential for slides in the aforementioned members occur in areas where the relatively bentonite free Verendrye Member crops out or where this member overlies the shale and bentonite facies of the DeGrey Member (Scully, 75). In this setting, the slides occur in the DeGrey member.

Joint systems in the shale play a very important role in the nature of groundwater flow through the shale and the stability of the shale. In some areas, continuous joints may occur, and where these joints are oriented parallel to ridges, verical flow to significant depths can occur, thus providing lubrication or hydraulic head to trigger slope failures.

Random orientations of beds that are broken or layered with bentonite strata tend to promote horizontal flow along the tops of the less permeable bentonite layers. This is due to the fact that the bentonite layers and bentonitic shale layers swell when in contact with water. This causes a decrease in strength of this unit, promoting instability. Block sliding commonly occurs where bentonite layers are present, and when thick bentonitic shales are present, rotation sliding may occur. Block sliding can also occur at the contact between the weathered bedrock and the underlying unweathered material.

Sliding can occur both during and after construction. The highest probability of sliding occurs when:

1. An occurrence of a landslide in the area has already been documented and construction can reactivate the slide near the toe or if fill is placed near the scarp.
2. The groundwater occurrence in the shale is at equilibrium in a particular area, and construction disrupts this equilibrium and initiates a slide.
3. New embankments or fills cut off the natural drainage in an area, causing more instability.
4. Weathered surficial material is removed making way for large amounts of water to enter joints or cracks.
5. The shale is deteriorating due to water flowing through the shale causing weathering.

Studies to determine susceptibility of slides need to begin with a study of the stratigraphy of the area, to determine whether any of the units that typically result in slope failures are present at the site.

Typically within the outcrop area of the Pierre, the areas of high landslide potential are localized. Therefore a number of methods are used to identify these areas. They may include:

a. Air photos interpretation and field reconnaissance
b. Resistivity and self potential measurements
c. Seismic refraction measurements
d. Drilling, sampling and Standard Penetration Tests
e. Analysis of the results of geotechnical and chemical laboratory tests

f. Analysis of the stress-deformation response of samples tested in undrained compression. (Scully 75).

Air photos can be used to identify large slides or areas with larger jointing. Smaller or older slides which are hard to discern by looking at an aerial can be seen during a field reconnaissance.

Field studies must contain landslide areas that show large sound blocks and highly weathered and degraded shales. Field studies in stable areas must investigate slopes with jointed shales and those with sound shales. This will determine the limits for the stable and unstable slopes and then other situations can be studied. Areas where the shale is at equilibrium before construction and in areas where the entry of water will increase must also be taken into consideration. These two factors will increase the level of instability already determined in an untouched area.

Self potential measurement as self potential voltage will be high and variations in the readings will be large in areas where water flow is present and weathering is occurring. In areas of old slides, the determination of slip face orientation is essential. These are noted by abrupt changes in penetration resistance and by changes in resistivity and/or self potential voltage. Areas which show low resistivity are areas which have high potential for landslide during construction. Additional information in the behavior of the shale can also be gained during the actual construction activities.

The use of laboratory analysis and other intensive study can indicate where measures need to be employed to reduce risk of slope failure. Water content and undrained strength tests are those tests that will give relevant information on the stability of the area. Additional information can also be gained from stress deformation curves, which show the behavior of the shale in different states of weathering and different types of jointing.

Several different tools to determine slope stability are required to fully understand an area. After the air photo and field reconnaissance has been performed, resistivity surveys and penetration tests have been conducted, the need for further study should be determined. In areas of high resistivity and erratic Standard Penetration Test values, siesmic refraction tests and rotary drilling should be performed in areas where arrival times are erratic and drilling fluids are lost. Sampleing to determine the amount of mineralization in joint fractures can help to evaluate the amount of water that has passed through these joints in the past.

Treatment of these potential slide areas depends on the types of slope it will be (cut or fill) and the time in which the slide may occur (during or after construction). Slides that occur during or after construction can be removed until more stable areas are reached. Where the flow of water in the unit has been interrupted or increased, underdrains can be installed to reduce the effect of water in the unit. Where slopes have been decreased which could cause a retention of additional volumes of water in previously higher flow areas, paved ditches and slope covers of less permeable material may be required in side hill cut and fill sections.

Avoidance of high slide areas is always preferred however this is not possible in all locations. However, if slopes are designed conservatively, drainage is increased in the areas needed and protection of the slopes by minimizing the infiltration of water has been used, the number of slides will be reduced.

Mitigation of problems associated with unstable slopes in the Pierre Shale is usually achieved by geotechnical engineering techniques applied to the problem areas identified by geological reconnaissance. Slope stability analyses, potential re-routing of the rail line to avoid the worst conditions, flattening of excavated slopes, groundwater drains or control structures, and retaining wall structures would all likely be called into play during detailed design.

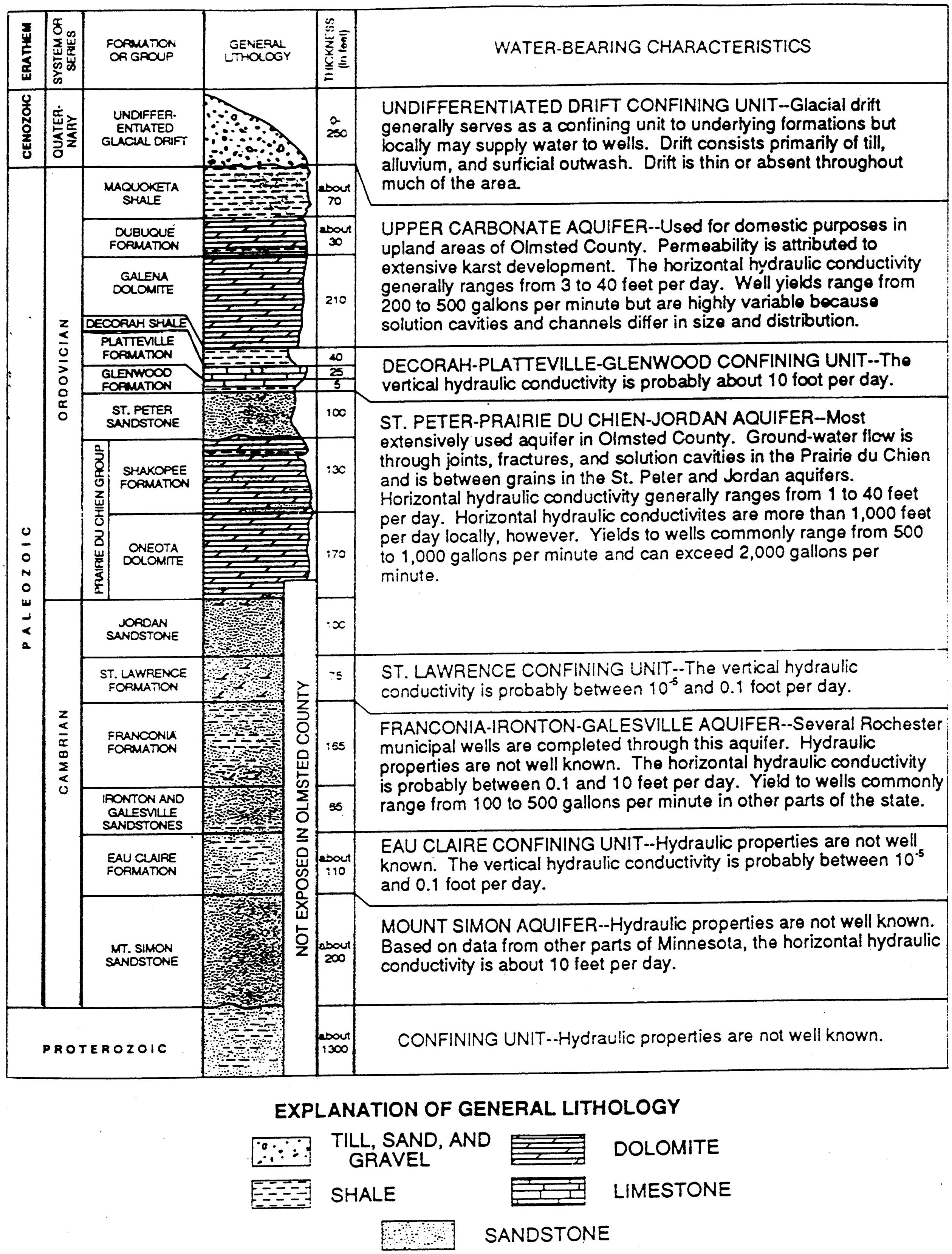
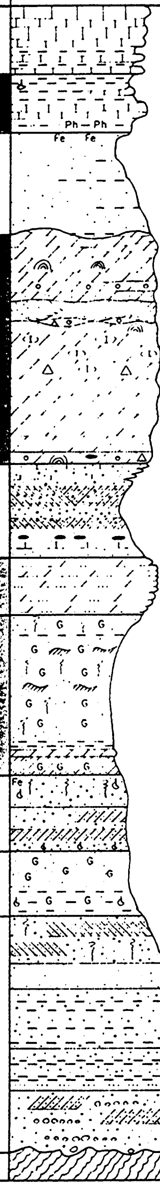


Figure 1. Generalized hydrogeologic column of regional aquifers and confining units, Olmsted County, Minnesota (Delin, 1991).

SYSTEM SERIES	GROUP OR FORMATION NAME	SYMBOL	LITHOLOGY	THICKNESS (feet)	DESCRIPTION
MIDDLE ORDOVICIAN	GALENA FORMATION	Og		60	Fine-grained fossiliferous limestone. Many shale partings in basal 15-20 feet
	DECORAH SHALE PLATTEVILLE Fm GLENWOOD Fm			45 20 4	Shale and thin interbeds of limestone. Commonly fossiliferous Fine-grained fossiliferous limestone Sandy shale
	ST. PETER SANDSTONE	Os		90 to 100	Fine- to medium-grained, poorly cemented, quartzose sandstone; basal contact minor erosional surface. Upper surface commonly iron crusted. Generally massive and unbedded
LOWER ORDOVICIAN	PRAIRIE DU CHIEN GROUP: SHAKOPEE FORMATION			90 to 115	Thin-bedded and medium-bedded dolomite with thin sandstone and shale beds. Basal 20 to 30 feet is fine-grained quartzose sandstone. Local red iron staining. Basal contact minor erosional surface
	PRAIRIE DU CHIEN GROUP: ONEOTA DOLOMITE			160 to 180	Thick-bedded to massive dolomite. Some sandy dolomite in basal 10 to 20 feet. Vugs filled with coarse calcite in upper part. Minor chert nodules. Upper part near contact with Shakopee commonly brecciated
UPPER CAMBRIAN	JORDAN SANDSTONE	€j		100 to 120	Sandstone. Top 30 feet is thin bedded and well cemented by calcite. Middle part is medium- to coarse-grained quartzose sandstone; generally uncemented and iron stained in outcrop. Basal 35 to 40 feet is very fine to fine-grained sandstone
	ST. LAWRENCE[1] FORMATION			50 to 75	Thin-bedded dolomitic siltstone. Minor shale partings
	FRANCONIA[1] FORMATION			140 to 180	Thin-bedded, dolomite-cemented glauconitic sandstone. Very fine to fine grained. Contains minor dolomite beds near base and shale partings throughout
	IRONTON & GALESVILLE SANDSTONES	€ig		90 to 120	Ironton: Poorly sorted, silty, fine- to medium-grained quartzose sandstone with minor glauconite Galesville: Fine- to medium-grained, well-sorted quartzose sandstone
	EAU CLAIRE[2] FORMATION	€e		90 to 125	Very fine to fine-grained sandstone and siltstone. Some is glauconitic. Interbedded shale
	MT. SIMON[2] SANDSTONE	€m		290 to 350	Fine- to very coarse grained, poorly cemented sandstone. Contains pebbles in basal 20 to 40 feet. Sandstone generally moderately to well sorted. Greenish-gray shale mottled with grayish-red in basal third of formation. Basal contact major erosional surface
PRECAMBRIAN[3]		p€			Biotitic granite gneiss in eastern part. Poorly known in west



[1]St. Lawrence and Franconia Formations undivided on map. Symbol: €sf

[2]Eau Claire Formation and Mt. Simon Sandstone undivided on map. Symbol: €em

[3]Precambrian shown only on sections

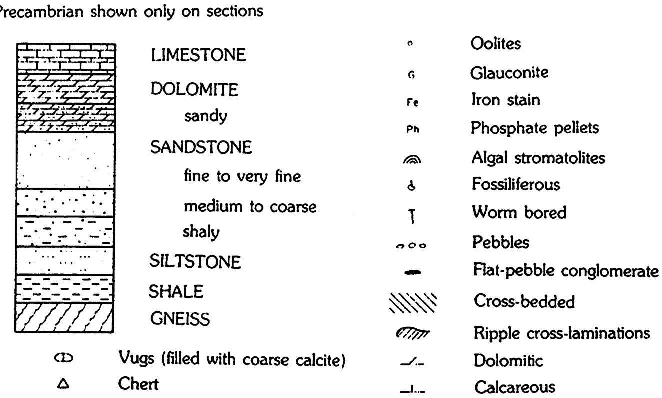


Figure 2. Generalized stratigraphic column of regional geologic groups or formations, Winona County, Minnesota (Balaban, N. H. and Olsen, B. M. eds, Plate 2, 1984).

ROCK UNIT		AQUIFER SYSTEM	HYDROLOGIC CONDITION	WATER-LEVEL RELATIONSHIPS
GALENA FORMATION		UPPER CARBONATE AQUIFER	MOSTLY DEWATERED	
DECORAH SHALE PLATTEVILLE FM. GLENWOOD FM.		CONFINING LAYER	NON-AQUIFER	
ST. PETER SANDSTONE		ST. PETER AQUIFER	MOSTLY DEWATERED	
SHAKOPEE FORMATION	PRAIRIE DU CHIEN GROUP	PRAIRIE DU CHIEN-JORDAN AQUIFER	MOSTLY UNCONFINED	Highest potentiometric surface; ←About 100 to 200 feet→
ONEOTA DOLOMITE	PRAIRIE DU CHIEN GROUP	PRAIRIE DU CHIEN-JORDAN AQUIFER	MOSTLY UNCONFINED	
JORDAN SANDSTONE		PRAIRIE DU CHIEN-JORDAN AQUIFER	MOSTLY UNCONFINED	
ST. LAWRENCE FORMATION		CONFINING LAYER	NON-AQUIFER	Potentiometric surface
FRANCONIA FORMATION		FRANCONIA-IRONTON-GALESVILLE AQUIFER	ARTESIAN EXCEPT WHERE DISCHARGING INTO VALLEYS	←About 150 feet→
IRONTON & GALESVILLE SANDSTONES		FRANCONIA-IRONTON-GALESVILLE AQUIFER	ARTESIAN EXCEPT WHERE DISCHARGING INTO VALLEYS	Lowest potentiometric surface
EAU CLAIRE FORMATION		CONFINING LAYER	NON-AQUIFER	
MT. SIMON SANDSTONE		MT. SIMON AQUIFER	ARTESIAN EXCEPT WHERE DISCHARGING INTO VALLEYS	
PRECAMBRIAN		UNKNOWN ? ?	UNKNOWN	

Figure 3. Sequence of bedrock aquifers, Winona County, Minnesota (Balaban, N. H. and Olsen, B. M. eds, Plate 4, 1984).

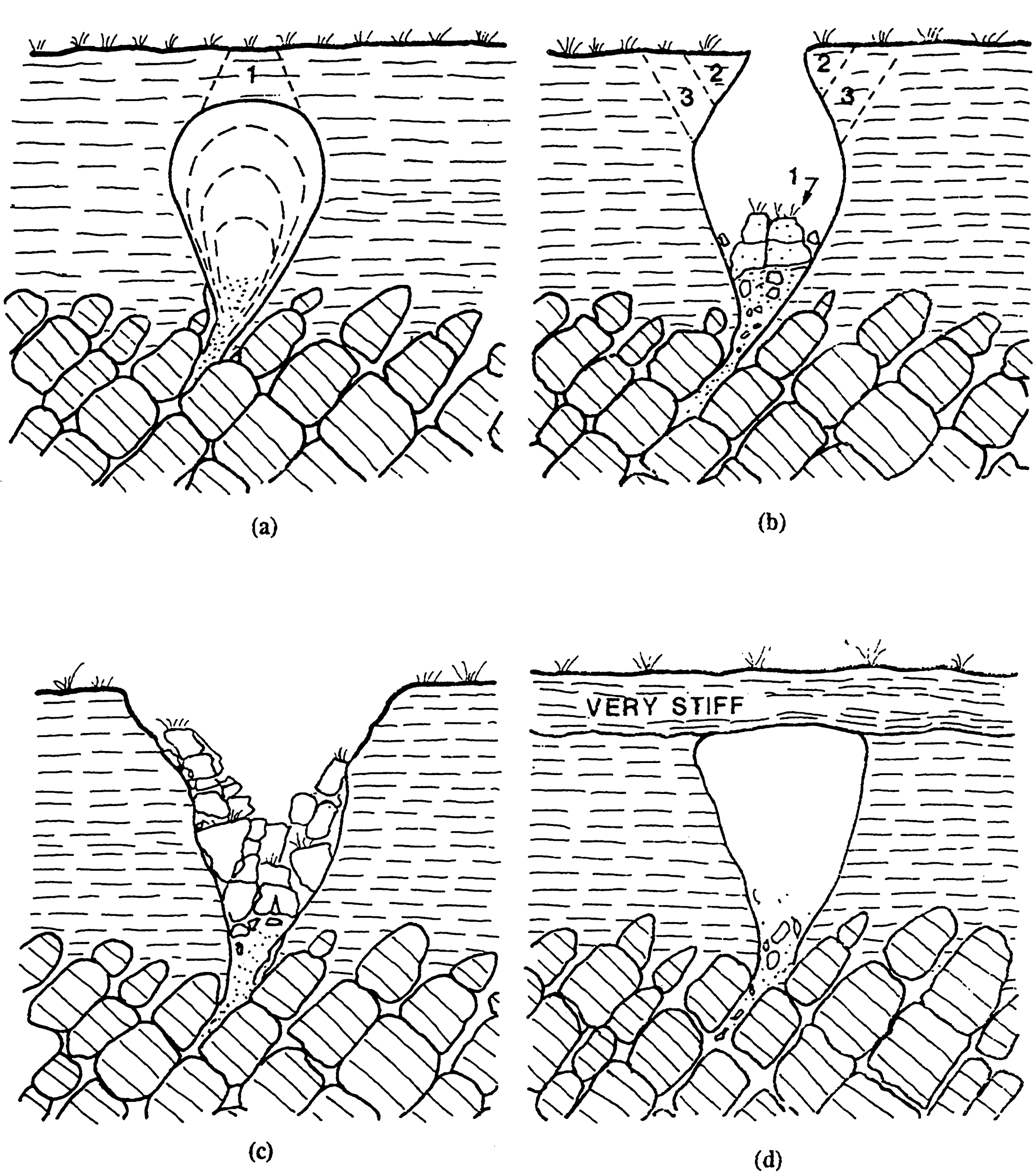


FIG. 3.9. Ravelling Erosion Dome Progression and Roof Collapse in a Cohesive Soil: a. Usual Inverted Tear-drop Shape with Potential Initial Dropout, 1; b. Initial Roof Dropout; Overhanging Rim and Successive Additional Dropouts, 2 and 3; c. Final Rim Collapse with Debris in Dome; d. Flat Dome Roof Beneath a Very Stiff Pedologic Horizon

Figure 4. Diagrams of soil dome generation and collapse (Sowers, 1996).

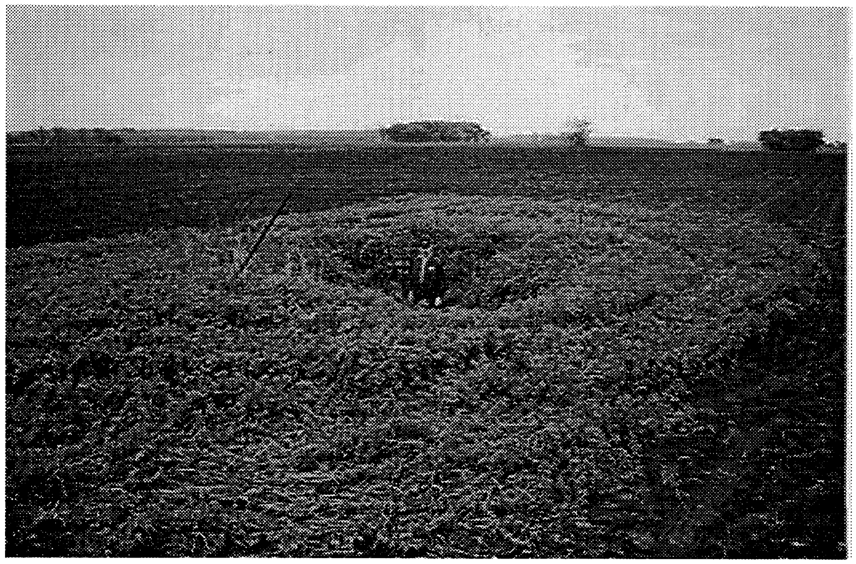


Figure 5.

Recently Formed Sinkhole

Figure 6.

Steep-Walled Sinkhole with Open Void at Base

Figure 7.

Closed Depression in Ground Surface

Figure 8.

Streamlines in Sand at the Bottom of a Sinkhole

Figure 9.

Bluff at Skyline

Figure 10.

Slope Failure on Ski Slope South of Skyline

Figure 11.

Slope Failure at Highway Cut South of Skyline

Outcrop	Influence
Upland Non-shale Deposits	
a) Sand and gravel Terraces, Glacial Outwash, Wind Blown Silts	Act as reservoirs for water, storing water for entry into joint systems beneath
b) Clayey Glacial Tills	Retard or prevent water entry.
Shale Layers	
a) Siliceous Calcareous Non-Bentonitic Shale	Permit water entry as the physical discontinuities do not close rapidly upon exposure to water
b) Bentonitic Shale	Retard or prevent water entry as any joints close as the bentonitic shale swells.
Physical Discontinuities	
a) Desiccation Cracks	Main means of entry in areas free of non-shale deposits and landslide masses, largest cracks form in grass-covered, weathered shale.
b) Faults Movement Cracks	Large scale physical discontinuities allow water to enter slide masses, (faults also exist in areas free of slides but their importance is not well understood)
Mineral Discontinuities	
a) Bentonite Layers	Where close to the surface these layers prevent or retard water entry
b) Marl Layers	Marl layers contain open joints; where exposed, these layers permit larger amounts of water to enter

Table 1. Water Entry into the Pierre Shale (Scully, 1975).

Factor	Influence
Physical Discontinuities	
a) Joints Partings Tectonic Faulting	Control vertical flow within shale undisturbed by sliding and transport horizontal flow
b) Movement Cracks Faults	Increase water flow into slide masses. Also may allow flow from slide mass retarding further movements.
Mineral Discontinuities	
a) Bentonite Layers	Retard vertical flow and create horizontal flow. (Spacing of beds control the continuity and spacing of the joints)
b) Marl Layers	Containing open joints horizontal flow increases in these layers, however, they do not prevent vertical flow
c) Thin Indurated Layers and groups of concretion	In eroded areas, openings develop in these more brittle layers which increase horizontal flow
Shale Layers	
a) Calcareous Shale	Contain open joints (some filled with gypsum) which increase horizontal flow
b) Siliceous Shale	Contain systems of joints for water flow which remain open during flow
c) Non-Bentonitic Shale	Contain long joints with large vertical extent, however, these joints are not open and do not permit large amounts of flow
d) Bentonitic Shale	Contain joints, but, retard flow as joints seal by swelling

Table 2. Factors Influencing Water Flow Through the Shale (Scully, 1975).

Member	General Description
Elk Butte	Bentonitic Shale with few mineral discontinuities
Mobridge	Calcareous Shale with layers of Marl and Limestone Concretions
Virgin Creek	
a) Upper	Bentonitic Shale
b) Lower	Alternating layers of siliceous shale and bentonite beds
Verendrye	Bentonitic Shale with numerous thin indurated layers limited small bentonite beds and some shale layers with high montmorillonite content
DeGrey	
Shale and Bentonite Facies	Bentonitic Shale with numerous bentonite layers
Siliceous Shale Facies	Siliceous shale with three or more bentonite layers
Crow Creek	5 to 10 foot Marl layer with thin 6 to 12 inch basal sand or silt stone
Gregory	
a) Upper	Less bentonitic shale with six bentonite layers
b) Middle	Non-bentonitic shale with numerous concretions, thin indurated layers and shells.
c) Lower	Increasingly bentonitic shale with Marl layers
Sharon Springs	Black carbonaceous shale with numerous bentonite layers.

Table 3. Stratigraphy of the Pierre Shale Formation (Scully, 1975).

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